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A review on lighting control technologies in commercial buildings, their performance and affecting factors

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ABSTRACT

Lighting constitutes a significant portion of building energy consumption. Automatic lighting control systems reduce energy consumption by decreasing operating time of lamps based on various factors like occupancy, time of day, availability of daylight. Various technologies exist that perform lighting control. These technologies differ in their input parameters, their control method, control algorithm, cost of installation, complexity of commissioning, etc. Each of the control schemes has a unique set of factors that affect their performance in terms of energy savings as well as user acceptance. This paper aims to investigate the various control system types, the development of their associated technologies, the savings reported from their application and the factors affecting their performance.

Contents

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1. Introduction

Energy efficiency is one of the main focuses of research in electrical engineering at the present time. The increased attention and study to identify more efficient and smarter ways to use electrical energy comes directly from the growing need to conserve dwindling global resources, as well as growing concerns over the environmental impact of the conventional energy sources. A decreased use of energy means less to pay for energy bills, reduced load on the grid and less environmental impact. Lighting is the most common and naturally the most constant form of load. It represents a significant portion of the total electricity consumption all building types, and it is more prominent in commercial buildings. For example, according the US Department of Energy, lighting load represents 14% energy consumption in commercial buildings on average [1]. Other studies show that average lighting load can be significantly higher in some cases [2]. A European study shows that in case of medium and large buildings, about 40% of the total electricity is used for interior lighting [3].

Commercial buildings hold great importance when it comes to energy consumption. Out of the total primary energy requirement of the United States, for example, over one-third is consumed by commercial buildings [2]. If office buildings are considered separately, the contribution of lighting energy demand on overall energy consumption can be 25–35% [4]. So, reduction in lighting load in commercial buildings can have significant positive impact in decreasing the electricity demand, which in turn helps reduce carbon footprint [5,6], which is a key focus for energy engineers at the current time. Taking the energy impact of lighting systems into perspective, various governments, international and regional organizations promote specific energy saving guidelines for lighting systems [7,8]. Hence researchers have been continuously thriving to achieve better efficiency in lighting, which means maintaining optimum lighting conditions using as less energy as possible.

Research shows significant savings from various types of lighting control schemes [9]. Manual lighting controls depend mostly on occupant behaviour, occupancy patterns, and general awareness about energy saving [10]. At the user level, lighting installations can be controlled by different types of switching systems. The basic conventional switching systems provide simple on and off options. Dimming regulators provide the users with the option to dim the intensity of the lamps, but in that case the lamps must be controlled by dimmable ballasts. More advanced electronic switches can be programmed to operate in different ways like toggling or changing intensity in steps. Advanced building automation systems provide more flexibility in terms of control by the user, as they offer the ability to implement computer controlled lighting systems. In such cases, the users can control the brightness level and other parameters right from their computer screens. Further, products are now entering the market, which allow to be controlled over internet communication using smartphone apps. These technologies provide new flexible ways to control the lighting scenarios for the user. But when it comes to automation of the switching or dimming process of the lights, there are several different technologies that work beyond the user end. These technologies vary based on the parameters they consider for the control of the lamps. This paper aims to discuss these technologies.

Automatic schemes vary a lot in technology and complexity. In a basic level, the automatic controls can be used to switch on or off the lights, and on a more precise level they can control the level of illumination based on requirement [9]. It needs to be remembered that any control scheme may not be suitable for application for any type of task. Different workspaces have different lighting requirements and widely varying occupant behaviour. Choice of lamps, luminaries and control schemes must be guided according to those requirements to ensure occupant satisfaction and productivity [11]. To successfully select the right lighting technology, the occupant behaviour of every type of room or building based on their type of activity must be surveyed. This occupancy pattern will then provide a picture about how the occupants of the room really use the energy in those spaces [12].

Including the pattern of usage by occupants, there are several other factors that affect the performance of control systems, and these factors may be particular to a certain type of control system. For instance, for occupancy sensors, time delay setting is a key issue which can have an impact on their performance; while for daylight-linked systems, choosing between switching and dimming or between open and closed loop algorithm can be decisive in the success of the implementation. Since each of the control systems uses different parameters in order to control the lighting, the affecting factors of these technologies are also different. Failure of properly understanding these affecting parameters can lead to improper commissioning of the lighting control systems and thus to unsatisfactory energy saving performance and poor user satisfaction. Hence, this literature review aims to investigate the affecting factors for each of these control strategies and review published works of research to determine the impact of changing these factors on the energy saving performance of the lighting control systems. The paper also discusses about current developing trends in lighting control and possible future work that can be achieved in this field.

1.1. Reducing lighting energy consumption

The factors that affect the overall energy consumption of the lighting system can be understood from the basic equation of electrical energy consumption:

$$W = P*T \text{ Watt hour (W h)} \tag{1}$$

where P is the installed lighting power in Watt (W) and T is the operating time in hours (h). It is obvious that energy consumption W can be reduced by reducing either or both of the factors P and T.

Installed lighting power (P) can be reduced using more efficient lamps. An efficient lamp produces adequate amount of lighting output (lux) using as less power input as possible. The lux to watt ratio of lamps is called luminous efficacy. The higher the luminous efficacy of the lamp, the more efficient it is in using its input power. By using lamps with higher luminous efficacy, the overall lighting load can be significantly reduced. The lighting load can also be reduced by proper lighting design. Task lighting method in lighting design provides necessary levels of light where the tasks are performed, while maintaining a lower ambient lux level in other areas.

Daylight-linked control systems play a role in reducing lighting power (*P*) by utilizing the level of available daylight in a room. Based on the daylight level entering a room or area, the daylight-linked lighting control systems either switch or dim the light fixtures to maintain adequate light levels required for the task performed in the room. In spaces where there is significant daylight penetration, lighting load can be considerably decreased by the control systems using switching or dimming method.

When it comes to reducing the operating hour *(T)* in Eq. (1), institutional scheduling system like time switches can be useful. Occupancy sensors detect the presence of occupants in the room and can switch off the lights when the control area is unoccupied. Thus the operating hours can be reduced, causing a reduction in lighting energy consumption.

In the upcoming sections, the various technologies in lighting control, their energy saving potential, the advantages and problems in using these technologies, as well as the issues that affect the performance of these systems shall be discussed.

1.2. Current use of control strategies

Studies have been performed to assess the current scenario in penetration of lighting automation systems in the market. According the market research, adoption of lighting automation is becoming a norm rather than something exceptional. Energy saving opportunities and increased awareness regarding energy efficiency positively influence installation of lighting energy saving technologies [13]. A study conducted by research farm Ducker Research addressed issues like driving factors for lighting automation usage, percentage of penetration of automation schemes, user satisfaction and preferences about the control schemes, etc. [14]. It is found that the rate of lighting automation usage is higher in the case of new constructions as compared to retrofits. According to the study, for example, 61.8% of newly constructed commercial offices use some form of lighting automation, while this adoption rate is 57.5% for existing offices. Higher educational buildings show a much better trend in using lighting automation, with 71.4% adoption for new constructions, and slightly less for retrofits. In newly constructed or under-construction offices, 65.4% floor space is covered by automated lighting. That value is 57.6% in higher educational facilities. In this case as well, retrofitted automation systems have less penetration than the new constructions.

As far as choice of automation technology is concerned, occupancy sensors are significantly ahead of scheduling and daylight sensors. For scheduling purposes, building energy management systems and time switches are both used commonly. But building managements systems are preferred for larger buildings, particularly for new construction projects, since the initial cost is much higher in this case and also the commissioning process is more complicated. Thus, for smaller buildings and retrofit projects, time switches are often used for scheduling due to comparatively lower cost and easier implementation. User satisfaction is slightly more in favour of scheduling systems like building automation and control panels than occupancy and daylight sensors, in terms of meeting expected energy savings and also reliability of the technology.

The control systems provide more advanced and intelligent performance when they are integrated with building automation systems [15]. Building automation systems provide increased flexibility for incorporating control schemes with light fixtures, as well as real time energy data for better energy management.

2. Occupancy-based control schemes

Among the control schemes used for lighting automation, occupancy sensor technologies have been used for a long time and are used widely [10]. The use of occupancy sensors is actually promoted by the North American and European codes for energy

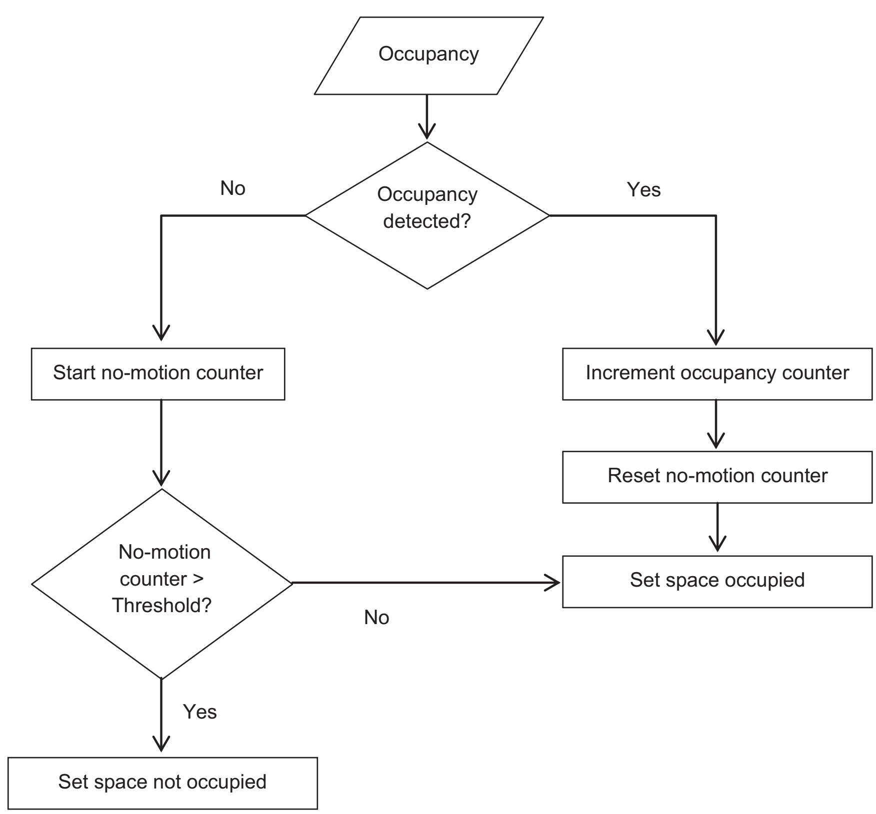

Fig. 1. Occupancy sensor algorithm [19].

efficient building development [16,17]. Occupancy sensors employ some sort of motion sensing technique to detect the presence of occupants in a given range of space, so the lights are switch on when it detects any occupant, and switched off when there is no occupant within a pre-fixed delay period. The technology of the sensor can be of different types and costs. Passive Infrared (PIR), Ultrasonic, Acoustic, Microwave type and other types are currently in use, and all of those have their pros and cons. Some are more susceptible to 'False-Ons' i.e. they are triggered on by a false movement coming from an object other than an actual occupant. Others have the reverse effect and they tend to turn off even in the presence of an occupant. Researchers have found that instead of relying on a single occupancy sensor for a room or area, the percentage of these errors can be significantly reduced by using multiple sensors together. They can be of the same type or, for even better detection performance, of multiple sensor technologies [18].

Despite the difference in the technology used to detect the motion, the underlying algorithm for the operation of the system remains pretty much the same. If motion from occupants is not detected, a timer, which is set during commissioning, starts counting. At the end of the counter, if the space is still unoccupied, i.e. no motion is detected by the sensor, the unoccupied state is set and the appropriate signals for turning the lights off is sent. If within this period any motion is detected, the counter is reset. The algorithm can be shown as in Fig. 1. [19].

2.1. Classification of occupancy-based control schemes

Based on the type of actions performed by the controllers, the scheme can be of two types:

1. Motion-based switching – Depending on the movement detected by the occupancy sensor, this system switches the lights on or off. When the area covered by the sensor is unoccupied for a pre-determined time interval, the lights are switched off. They are switched on as occupancy is detected by the sensors. Quite naturally, the lower the delay setting, the more savings can be achieved. But in some cases, particularly in rooms where the incoming and outgoing of occupants is irregular, shorter delay times can cause dissatisfaction for the users of the room, as they often find themselves coming into completely dark workspaces. On the other hand, longer delay periods reduce the energy saving potential from the control system. So it is obvious that before implementing the control system, the occupancy behaviour pattern of the room or area must be studied well in order get the optimum balance between energy savings and user satisfaction. This type of scheme is more preferable for single offices [20].
2. Motion-based dimming – This system can dim the lights when no occupancy is detected for a set time interval. The light level, to which the lights will be dimmed to in case of no occupancy, can be pre-set [20]. This is more useful for offices where users are not satisfied to return to the workplace to find it completely dark, and the lights come on as they come into the office. This scheme, although saves less energy than the previous scheme, can be more satisfying to users, as the transition from non-occupied to occupied state of lights is much more smoother than an abrupt on-off state change. Compared to switching, this system demands higher installation cost due to the necessity of electronic dimmable ballasts to control the light output of the lamps.

This type of lighting control can be particularly useful in landscape offices. If the room is divided into multiple occupancy controlled zones, a general illuminance level can be maintained throughout the office floor where the workspaces are unoccupied, and adequate level is provided for present occupants. This provides a smoother contrast between occupied and unoccupied spaces, instead of completely bright and dark spaces which can cause visual and psychological discomfort [21].

2.2. Occupancy detection techniques

Based on the occupancy detection technique, there can be several types of sensing system. Passive Infrared (PIR) and ultrasonic sensors are widely used detections systems. New technologies like Radio Frequency Identification (RFID) and digital imaging are also being developed and gaining attention. These technologies will be discussed in the following sub-sections.

2.2.1. Passive Infrared (PIR) sensors

Passive Infrared (PIR) detection systems rely on detecting a change in the temperature pattern in the sensor's detection zone [18]. The detection in this case is done by a Pyroelectric detector. Since the sensor does not emit any energy itself, it is called a 'passive' sensor in this case. Sensitivity of these types of sensors is dependent on the distance of the subject from the sensor. The further the subject or moving warm body, the less accurate is the detection by the sensor. A common complaint regarding this type is sensor is that it is prone to 'False-off' errors, i.e. the lights are switched off despite occupancy. This can happen due to detection principle of the PIR sensors. There are gaps in the sensing zone of PIR sensors, which can be significantly wide as they go further from the sensor. Movements within these gaps may not be detected properly by the sensors [22].

2.2.2. Ultrasonic sensors

The second most prominent occupancy sensing technology is the Ultrasonic occupancy sensor, which has been in development and practical implementation for a long time [23]. These devices work based on the principle of Doppler Effect. They emit ultrasonic sound waves, and compare that with reflected signals. When an emitted ultrasonic sound wave is reflected off a static object, the reflected signal will have the same wavelength as the emitted signal. But when the object is moving, the wave length of the reflected signal will be different. This principle of Doppler Effect is the underlying principle of motion detection by ultrasonic occupancy sensors. A key advantage of this technique is that ultrasonic waves are reflected by room surfaces, so ultrasonic occupancy sensors do not require a field of vision as compared to the PIR sensors. This means ultrasonic sensors are much more effective in detecting occupant motion, which can be particularly useful in indoor spaces. Reliability of ultrasonic sensors in detecting presence over long distances have been proven by research [24]. The added sensitivity also causes problems in this type of sensors. Movements coming from activities in the room other than occupant movement can trigger the sensor. Thus, 'False-on' errors are common in ultrasonic occupancy detection. In some cases it can be so sensitive as to pick up movements of leaves outside the window and even air turbulence from office air conditioners. Another disadvantage, like the PIR sensors, is that the detection accuracy gets lower when subjects are further from the sensors, due to the gradual weakening of the reflected ultrasonic waves.

2.2.3. Radio Frequency Identification (RFID)

Lighting control using Radio Frequency Identification (RFID) as a method for detecting occupancy is gaining focus in lighting research. RFID tags are commonly used for personnel identification purposes in offices. Due to the small size and affordable cost of tags, they are installed inside ID cards for tracking entrance and exit times of office employees, students, etc. Using this existing technology, research suggests that improvement in current

occupancy detecting methods can be achieved. Some researchers suggest using RFID as a supportive technology to existing occupancy detection scheme. By the aid of the added information from the RFID system, the shortcomings of the existing system can be minimized. Manzoor et al. [25] proposed the use of passive RFID detection to aid the detection process of the Passive Infrared (PIR) system already installed in an open plan office space. As discussed previously, PIR systems are susceptible to 'False-off' errors, which they proposed to minimize using the data from RFID system. Also, they proposed to minimize the Time Delay (TD) setting of lighting control scheme to further increase energy savings. Since passive RFID tags are dependent upon the RFID readers for power, the researchers in this case developed an RFID 'gateway'. The gateway records occupancy density and pattern based on flag statuses, which change as users enter and exit the control zone.

Given that the RFID tags are person-specific, the RFID detection system not only provides occupant density, but also occupant profiling, i.e. it is known which occupants are using the zone at a given moment. When the information of the designated workspace of each user is programmed into the system, the control scheme can then control the lamps relevant to the occupant entering or exiting the room. But this simple gateway approach can sometimes fail to register a tag, due the unreliable nature of passive RFID signals, thus considering the zone to be unoccupied even when it is occupied or vice-versa.

The shortcomings of passive RFID system can be overcome by using active RFID. Active RFID tags have their own miniature power source, which provides for better localization of occupants. Besides sharing the advantages of passive RFID as occupant density and profiling, active RFID can be also used for localization of occupants based on the Received Signal Strength Indication (RSSI), which varies based on the distance of the occupants (tags) from the reader. But active RFID has its own set of problems as well. The received RSSI can be affected by multiple factors like reflection, diffraction and transmission of radio waves, which is known as Multipath Effect in radio communication studies. The active signals can also be misinterpreted due to positioning of furniture, doors and windows, the pattern of occupants' usage of the room, etc. To counter these disadvantages, Zhen et al. [26] propose the use of multiple readers, thus reducing the probability of error in localization by one reader. They also suggest that instead of point to point localization of occupants, a more flexible zonal positioning can be used. Multiple readers in their case would also increase the reliability of the RFID signals, which is often seen as a problem. The system they developed proved to be 93% accurate in localizing the occupants to a specific zone.

2.2.4. *Occupancy detection using imaging*

The conventional occupancy detection techniques have seen a lot of research to increase their accuracy in detecting presence, as discussed in the previous sections. However, those systems are still not free from false errors. To develop a novel occupancy detection approach to minimize false detection and non-detection in occupancy controlled lighting systems, researchers are focusing on imaging techniques. Using cameras as sensors to detect presence of occupants, some researchers are trying to find a viable alternative to existing presence sensors that would be more accurate.

Liu et al. proposed a system [27] that would take advantage of surveillance cameras that exist already in many rooms. They have developed an algorithm which takes image frames from the static surveillance cameras installed in open plan office room and detects presence of human heads. The system was trained to detect human heads by feeding it with numerous images containing and not containing human heads. The resultant system proved to be efficient and accurate in determining human presence. In a similar work, Benezeth et al. [28] developed a system which takes video information from a camera to subtract the background and develop a background model. Using this model the tracking and recognition of occupants in the video frame can be performed. The researchers have illustrated their algorithm as in Fig. 2.

Other researchers developed an image based control systems [29,30] where they used CMOS based cameras that can provide luminance information. Such a system can provide more flexibility of usage besides just occupancy detection, like providing luminance information of a space for proper daylight harvesting and shading control. The information from a single camera can be further used for security purposes and fire detection, which can make adoption of the detection system more feasible financially. Their research thus suggests that a single camera can combine the applications of multiple separate sensors effectively.

2.3. *Savings from occupancy-based control*

Savings reports can vary based on which type of occupancy control has been implemented. Roisin et al. made a comparison between occupancy based switching and dimming systems and found that 8.7% savings can be achieved with switching, while a slightly higher 11% is achieved using dimming systems [20]. The sensors they had used were of the infrared type.

Richman et al. [31] used light loggers and ultrasonic occupancy sensors to calculate savings in lighting systems. Their study included 141 sample spaces. They used several different time delay settings to observe its effect on savings. Depending on the time delay which varied between 5 and 20 min, the research reported savings ranging from 50% to 3% respectively for private offices, and for restrooms, 86–73%. The effect of delay setting on achievable savings can be clearly understandable from this study. Savings from occupancy-based controls from previous studies are shown in Table 1.

Different types of rooms included in the three categories in Table 1 are: Offices: open plan offices, private offices, computer-based research labs. Educational: classrooms, experiment labs.

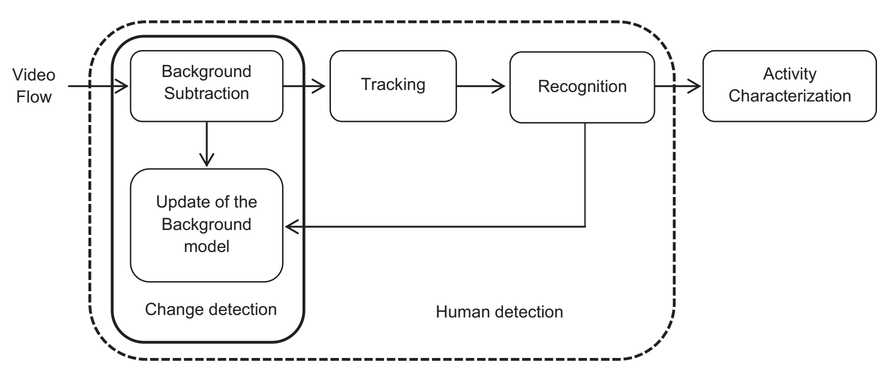

Fig. 2. Occupancy detection algorithm using video imaging [28].

Infrequently occupied spaces: break rooms, conference rooms, storages, and warehouses.

2.4. Factors affecting performance of occupancy-based control

Commissioning of occupancy sensors need to be taken very seriously in order to achieve satisfactory performance from them. First of all, there needs to be a proper understanding about the occupancy pattern of a room/area before implementing occupancy sensors. It must be understood that not all rooms may be suitable for occupancy detection in the first place. If the room is constantly occupied by people without any significant breaks throughout the activity period, a simple timer switch may be more appropriate than occupancy detectors. Occupancy detection is most useful for spaces where the occupancy in infrequent and/or irregular. Then, if a room is found to be suitable for occupancy sensor implementation, proper assessment of the usage pattern of the room, size of the room, activity areas, etc. must be studied for proper commissioning. Based on these studies, the (a) Time Delay, (b) sensitivity of sensor and (c) positioning and coverage zone of sensor must be tuned. The effects of Time Delay, Sensitivity and coverage area on the overall performance of occupancy based lighting control systems are summarized in Table 2.

2.4.1. Effect of Time Delay (TD)

A key factor that affects the energy savings achieved from occupancy sensors is the time delay settings. After a space is detected to be unoccupied by the occupancy sensors, the control system waits for a pre-fixed amount of time before it turns off the lights. This is known as the Time Delay Setting of the occupancy sensor. This is done to minimize frequent switching of lights in case of occupants leaving their space only for a short period of time. Frequent switching in these cases can also be very disturbing for the occupants [37], and found to have led to complaints regarding the control system. Obviously the shorter the time delay setting, the higher the energy saving possibility by reducing light usage time. But on the other hand, frequent switching of lights can hamper the longevity of the lamps, and also can be annoying to the users of the room, which can ultimately lead to decommissioning of the control system altogether. So it is clear that a balance need to be achieved between energy savings, product reliability and user satisfaction.

It is understandable that higher savings can be achieved by reducing the time delay. Von Neida et al. [33] conducted a study to determine the change in energy savings due to change in time delay. The study was extensive in coverage, which included rooms of varying occupancy types such as private offices, classrooms, restrooms, break rooms and conference rooms. Using simulations for 5,10,15 and 20 min delays, the appropriate savings possibility was calculated. It was evident from the results that there was a significant difference in savings between the maximum (20 min) and minimum (5 min) time delay setting. The relative change between time delay and energy savings can be seen in Table 3.

Some researchers argue that setting a fixed TD for all time in not suitable, since the activity level of occupants can vary person to person, as well as time to time. So they suggest a dynamic time delay setting. Garg and Bansal [38] proposed a smart adaptive occupancy sensor which can learn the variation of the activity level of the occupants, and change the TD of control system accordingly to provide maximum savings while reducing false error probability. So in their system, TD is not a fixed parameter set during commissioning, but a dynamic parameter which changes according to activity level. Their study resulted in 5% additional savings as compared to fixed TD occupancy control. Leephakpreeda also proposed an adaptive TD system [39], where the TD is determined by Grey prediction [40] using data about the users' past activity.

Since occupancy sensors can reduce overall load, they also reduce the demand of electricity. So a change in delay setting will also have effect in demand reduction. For example, according to the study of Von Neida [33], by reducing time delay from 20 min to 5 min, demand savings can be increased from 20% to 31% in private offices, and from 17% to 31% in case of restrooms.

2.4.2. Effect of occupancy pattern

Apart from the significant effect of reduced time delay setting on energy saving, another factor apparent from the results of Tables 1 and 3 is that the difference in savings will depend on the occupancy pattern of the rooms. The more infrequent or irregular the occupancy of a room, the higher the savings achievable from reduced delay settings. For instance, since classrooms are occupied in a regular pattern, the difference in saving by reducing delay setting from 20 to 5 min is just 6%, while the difference in the case of rest rooms is 13%, as restrooms are infrequently occupied by users. The study of Richman et al. [31] also suggests that the effect of TD on savings depends on the duration of occupied and unoccupied periods. The longer the unoccupied duration, the less is the influence of TD on energy savings.

3. Daylight-linked lighting controls

For buildings or rooms with provision to receive daylight, the lighting control schemes that are linked to daylight availability can provide the maximum amount of savings, given that the factors related to daylight availability like orientation, obstacles are in favour [9]. Rooms with adequate daylight penetration can benefit from using the available daylight, complementing the electrical lamps to provide adequate light levels [41]. Daylight-linked controls can either be used to switch lights on or off, which is more applicable for outdoor and common space light fixtures, or can be used in combination with dimmable electronic ballasts to provide the required artificial lighting level when daylight is present [2,41]. In case of outdoor common spaces like sports facilities, hallways, parking lots simple setups of daylight controlled on–off switches can be used. This would not only ensure that the lights are turned off during day time, but would also make manual supervision of lights unnecessary and save labour time.

3.1. Human impact of daylight presence

The human impact of daylight in workspaces is also an important factor to consider. Visual comfort is a key factor in increasing overall of quality of life of humans inside any building [42]. Apart from providing energy savings by reducing lighting load, presence of daylight has been proven to boost productivity and visual comfort [43–45]. Glare-free daylight is considered to be a complement to electric lamps by occupants. Study suggests that in such scenarios, users will utilize the daylight by dimming the artificial lights, if they are given that option [46]. But direct sunlight entrance or reflection from surfaces can create glare, causing discomfort and even eye strain [47]. Glare is a sensation that occurs when the luminance level of the visual field is higher than the luminance level human eyes are adapted to [48]. To counter this problem, some daylight control systems include automated window blinds to maintain appropriate amount of daylight entrance to ensure lighting as well as visual comfort by reducing daylight glare [49,50]. Excessive daylight entrance may also increase the heating of the room, thus increase cooling load for the air conditioners. Similarly, large window areas will allow more heat loss in cold weather [51]. Ghisi et al. [52] suggested an

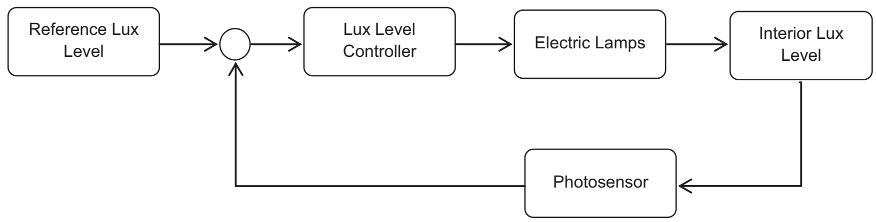

Fig. 3. Daylight-linked closed loop algorithm flowchart.

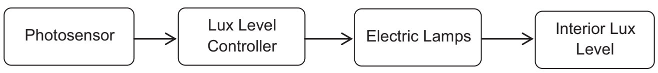

Fig. 4. Daylight-linked open loop control system.

ideal window area to ensure optimum daylight entrance that would strike a balance between lighting energy saving and reduction of heat from daylight. To ensure maximum utilization of daylight availability while providing visual comfort to the occupants, Parise and Martirano [53,54] suggest that daylight and electric lights cannot be considered separately. Instead, daylight infiltration, shading, electric lighting control and design must be recognized as parts of the lighting system as a whole from the beginning of a lighting project.

3.2. *Different methods of daylight-linked control*

Daylight-linked lighting controls can be divided into two types based on how they control the lighting system: (1) Daylight-linked Switching and (2) Daylight-linked Dimming [2].

Daylight-linked switching can control the lights by switching between 'On' and 'Off' states based on available daylight. There may also be multi-level switching. For instance, based on the level of available daylight in a particular control zone, 33%, 50%, 66% light of that zone may be switched off. These states are between the 100% on and 100% off states. Dimming systems control the lamp outputs continuously using dimmable electronic ballasts. Dimming requires dimmable ballasts to maintain the illuminance level of the lamps, so it is more expensive than switching system.

Daylight-linked systems can also be divided based on the algorithm of control, i.e. (1) Closed Loop and (2) Open Loop systems. A closed-loop system continuously detects lux levels of the control zone, which includes light from both daylight source and lamps. The change in the light levels of the lamps due to the availability of daylight is fed-back to the control system continuously, and it can make necessary adjustments based the feedback. Thus it makes a closed loop. Flowchart of a closed loop algorithm is shown in Fig. 3.

On the other hand, open-loop systems does not receive any feedback from the level of electrical lighting, it only detects available daylight levels. Based on the level of available daylight, it sends corresponding signal to the controller to provide corresponding lamp output. Flowchart of an open loop control system is shown in Fig. 4.

Illumination engineers are constantly putting effort on developing advanced algorithms [55,56] that would ensure best utilization of daylight for energy savings. Some researchers have also included control of window shades in the overall control algorithm to incorporate both energy savings and visual comfort [57].

3.3. *Savings from daylight-linked controls*

Numerous studies have been performed to determine the energy savings potential of daylight-linked lighting control schemes. These studies vary based on the type or room where the control is implemented, the method of lighting control and also the methodology of research. Savings reported from a few such studies are presented in Table 4.

It should be noted that the savings reported in Table 4 are measurements from actual implementations of daylight-linked control systems. There have been substantial studies performed on the estimation of energy savings from simulations or other evaluative analyses. The consistency of the estimated energy savings and measured savings can be widely varying, since daylight linked controls depend on many factors that can be difficult to simulate with precision [9]. Li and Tsang [62] used the RADIANCE lighting simulation software to simulate the daylighting scenario of a corridor. Energy savings estimations were also made based on the illumination. The results of their simulated estimations were compared with on-site measurements. The results showed that for most part the energy savings were overestimated. The discrepancy was much less for periods when the energy saving achieved was pretty large. They concluded that the difference between modelled and measured data was due to several factors as occupant behaviour, fluctuation in sensor light detection and inaccurate simulation of closed-loop control scheme. On the other hand, other researchers have found daylight simulations to be reliably accurate. Krarti et al. [63] developed a method of analysis that takes the factors affecting daylight availability into account, i.e. building geometry, window area and window type. Their approach provided energy savings estimations that agreed well with experimental measurements. Ihm et al. [64] further validated the estimations from this method. To enhance the accuracy of daylight control simulations, Bourgeois et al. [65] proposed adding advanced behavioural models to incorporate occupancy pattern predictions into the simulation.

3.4. *Factors affecting performance of daylight-linked controls*

Despite the high initial cost compared to scheduling or occupancy based controls, daylight-linked lighting controls can still be economically feasible due to high energy savings potential. But successful implementation of a daylight harvesting scheme depends on several factors. Lack of proper study of the room or area, occupant behaviour and the properties of the different control technologies will lead to a poorly commissioned lighting control system. Such a system either provides very low energy savings which leads to long payback period, or can be obtrusive to the users and lead to user dissatisfaction and consequent decommissioning. So the aspects affecting the performance of daylight-linked control systems must be understood. Key factors are discussed in the following sections.

3.4.1. *Daylight availability*

Total available daylight to any particular room will depend on several issues, i.e.

(a) *Sky condition:* Different sky conditions will have different effects on daylight availability and thus savings from daylight controls [21]. Since sky conditions change based on time of the

Table 1
Savings from occupancy based controls.

Room type	Research method	Time delay	Savings (%)	References
Offices	Field study	20–2 min	3–84	Richman et al. [31]
	Retrofit project	15–7 min	10–19	Floyd et al. [32]
	Field study	20–5 min	28–38	VonNeida et al. [33]
	Experimental	20–15 min	20–26	Jennings et al. [34]
	Field study	–	35	Galasiu et al. [35]
	Pilot project	–	35	Hughes et al. [36]
Educational	Retrofit project	10 min	11	Floyd et al. [32]
	Field study	20–5 min	52–58	VonNeida et al. [33]
	Field study	20–5 min	47–60	VonNeida et al. [33]
Infrequently occupied spaces	Field study	20–2 min	46–78	Richman et al. [31]
	Field study	20–5 min	17–50	VonNeida et al. [33]

Table 2
Effects of different parameters on occupancy control performance.

Parameter	Too high	Too low
Time delay	Less savings	Reduced lamp life due to frequent switching, Possible user dissatisfaction
Sensitivity	'False On' – detecting false movements coming from sources other than occupants, thus keeping lights on	'False Off' – failure to detect occupants, thus turning lights off despite presence, resulting in user dissatisfaction as well as unnecessary switching
Coverage area	Too large Detection of movement from adjacent space through doors/windows, thus keeping lights on unnecessarily	Too small Results in undetected zones in the workspace, where occupants are not detected despite presence

Table 3
Effect of Time Delay on energy savings.

Room type	Energy saving (%)	
	20 min delay (max)	5 min delay (min)
Classroom	52	58
Private Office	28	38
Conference Room	39	50
Break Room	17	29
Restroom	47	60

year or seasons, change in energy savings in daylight-linked lighting control can be observed throughout the year [60]. Overcast skies are considered to be the most unfavourable for daylighting. And since sky conditions depend on the local climate, which in turns vary based on location, the geographic position of the building must also be considered for assessing daylight availability [66].

(b) *Window properties:* Despite having supportive location to receive daylight, inappropriate positioning of windows may reduce daylight penetration. Proper window placement to ensure good daylight harvesting opportunities is usually done in the architectural design phase for new constructions. Orientation, area of window and window type i.e. type of window glazing can directly affect daylight availability of buildings [63,67].

(c) Obstructions: Trees, adjacent buildings, billboards or other structures can obstruct daylight entry through the windows [43]. This particularly happens if daylighting is not taken into consideration at the time of a building's architectural design.

3.4.2. *Selecting proper control method*

Based on the multiple affecting factors, engineers must choose proper control method to ensure optimum performance from daylight schemes. Selecting between daylight-based switching and dimming, and also between open and closed loop algorithms, are important steps for successful implementation.

Switching vs. dimming: Several factors determine which of the two methods is suitable. Cost of installation of the systems is one of the key driving factors in adoption of the technologies. The effectiveness of the systems will also depend on the pattern of daylight availability in the room throughout the day. Occupant behaviour of the room, i.e. how the users of the room use the space in terms of their movement, type of task, frequency of entrance and exit, etc. can severely affect the performance and savings of the daylight-linked system. As compared to switching controls, dimming of electric lamps show no negative effect on lamp life [68]. There are several advantages and disadvantages of using switching or dimming system. Comparison of these factors between switching and dimming systems are concisely presented in Table 5. All these factors must be considered and the application space thoroughly studied before implementation and tuning of the control scheme.

Open-loop vs. closed-loop systems: Choosing open or close loop system and placing the sensors accordingly is essential for successful commissioning. When the sensor is used to control a single control zone or comparatively small areas, like private offices, closed loop systems can be very effective. When the goal is to control multiple control zones with a single sensor, open-loop system is more preferable. Open plan office spaces are good targets for open-loop daylight system implementation.

3.4.3. *Proper tuning of control parameters*

Daylight schemes can fail due to inappropriate tuning of the control system. Proper tuning depends on the following:

(a) Suitable lux levels and delay settings: The control schemes will maintain a pre-set level of light intensity from the lamps based on the available daylight in the control zone. The lux level setting must be properly set to make sure adequate level of light is provided to the users at all time, notwithstanding daylight availability. Attention must be given to setting a 'deadband', a range of lux levels through which lamps will

Table 4
Savings from daylight-linked controls.

Room type	Control method	Research method	Savings (%)	Reference
Office	Dimming	Pilot project	20	Chung et al. [58]
	Dimming	Field study	20	Galasiu et al. [35]
	Dimming	Experimental	30	Sertaç et al. [56]
	Dimming	Pilot project	25	Guillemin et al. [57]
	Dimming	Pilot project	20	Hughes et al. [36]
	Dimming	Pilot project	27	Jennings et al. [34]
	Dimming	Pilot project	9–27	Rubinstein et al. [59]
	Dimming	Experimental	31	Onaygil et al. [60]
Classroom	Switching	Experimental	23.4–65.3	Cheung et al. [2]
	Dimming	Experimental	19.8–65.5	
	Switching+Dimming	Experimental	49.270.4	
Indoor open space/atrium	Switching	Pilot project	11–17	Morad et al. [61]
	Dimming		46	

Table 5
Comparison between daylight-linked switching and dimming controls.

Factors	Switching	Dimming
Suitable daylight condition	Contribution of daylight is significant, and daylight is consistent throughout day hours	Contribution of daylight is variable throughout the day
Suitable occupant activity	Occupant behaviour is not stationary, in circulation areas or common spaces. Task performed is not critical. Example – hallways	Occupants performing critical tasks in particular areas of the space, like offices
Advantages	• High savings in suitable areas • Low initial cost compared to dimmable systems • Relatively easy installation	• High savings in variable daylight • Gradual change between light levels, thus less obtrusive to occupants • Greater accuracy in control
Disadvantages	• Less accuracy in control • Prominent change in lighting state causes less user acceptance	• Higher initial cost • Requires precise tuning for optimum performance

not be switched, to make sure the switching is not frequent or disturbing to the users [2]. There are also two different delay settings for daylight switching. One for the lights to switch on, which is usually short, and another for switching lights off, which is longer. This is done in order to make sure adequate light is always provided to the users of the control zone, as well as to reduce frequent switching of the lights which can have negative impact on lamp life.

(b) Placement of sensor: Improper placement of photosensors can lead to failure of daylight harvesting project. The ideal location of the photosensor would be the task surface, but such a placement is not practical. Usually the photosensors are mounted on walls or ceilings. In some cases, they are built-in with the lamp fixtures. The critical issue for successful placement is to make sure the placement of the sensor is such that it detects a sample of daylight that best represents the daylight availability of the task surface in the control zone [69]. With such a placement, the photosensors would detect the daylight as if it is placed on the task surface. The sensors must be placed in such a way that it does not receive direct sunlight or any source of external glare. In that case, the detected daylight level will not be representative of the available daylight on the task surface. Similarly, placing the sensors far too deep into the room where the daylight penetration is significantly less than other areas in the control zone would be inappropriate. Placement of photosensors would also depend on whether the control system is open or closed loop [2]. Since in close-loop system the sensor needs to detect combined light levels on the task surface, the placement of the sensor must be such that it can detect the impact of both daylight and artificial lights. On the other hand, since open-loop system only takes daylight into consideration, the sensors must be placed in such a way that it only detects the level of daylight and not the lux levels due to the electric lighting.

4. Lighting control by time scheduling

Lighting control systems based on scheduling operate on very simple principle based on fixing an operating time of the light fixtures. The lights that are controlled by the control system are switched on and off based on a pre-fixed schedule. Scheduling systems are based on time, so it is useful in areas where the occupancy pattern is accurately predictable [66]. Rooms or spaces where events take place in very specific periods of time are perfectly suitable for application of scheduling systems. For instance, a classroom may have a fixed routine to hold classes from 9:00 AM to 1:00 PM, and then after a 1 hour break the classes resume from 2:00 PM to 5:00 PM. In such a classroom, a simple time switch may be used to turn the lighting system on during the time when the classes are scheduled to be held, and turn the lights off during lunch break and after class hours.

Scheduling can be done using simple control devices called time switches or time clocks. Fixed routine indoor areas, common spaces and outdoor lightings are appropriate targets for time switch use. Time switches can be manual mechanical devices, but more advanced digital versions are also available. Some digital time switches can be programmed via personal computer interface to run through a daily, weekly, monthly or even annual cycles. So, as an example, apart from maintaining daily schedules, they can be programmed to turn off the lights completely during weekends and public holidays. For application in indoor rooms

or spaces, an override capability is usually provided for the users in case of out of pattern usage of lights. Due to these flexibilities and their relatively affordable cost, time switches are attractive options for energy management in places with strict occupancy patterns, particularly outdoor areas.

Scheduling controllers can be stand alone, or they can be integrated in lighting control panels. Lighting control panels are central control systems for automation of lighting of multiple rooms or floors. These panels contain relays for the numerous loads controlled by the panel. Through the lighting control panel, control zones can be easily marked to be regulated by scheduling, occupancy detection or other control systems. Control panels have internal scheduling ability which can be programmed via PC connectivity. Control panels can be particularly useful in maintaining different schedules for different areas of the building that follow the same routine.

For user acceptance of time schedulers, override capability must be provided to make sure the users can use the lights beyond scheduled periods if the need arises. Multilevel switching should also be employed to make sure the users or not exposed to complete darkness suddenly. Advanced time clocks will flicker the lights to warn the users of imminent shut off, and they are given the window of opportunity to override the scheduling. In case of an override, the time switch should automatically return to scheduled mode after a certain time [70].

Properly commissioned time-based control systems can provide substantial savings. Rubinstein et al. [59] reported savings in office building applications between 10% and 40%. Scheduling systems are commonly used in combination with other control systems like occupancy sensors and photocells as well. A few savings reports from such combinations are mentioned in the following chapter.

5. Mixed control system

As shown in the previous discussion on the lighting control schemes currently in use, each of these technologies has their unique characteristics. A particular control scheme may give better performance in a certain scenario over other schemes, but it may not give similar performance in other situations. These technologies often fail to provide satisfactory performances due the shortcomings associated with that particular technology. In order to overcome these disadvantages and ensure maximum amount of savings without compromising user satisfaction, researchers have experimented with combinations of multiple types of control schemes in one system. It has been seen that combining technologies together gives substantial improvements in performance in terms of accuracy and energy saving (Table 6).

6. Current trends and future possibilities

Current research in the field of lighting controls is further pushing the possibilities of energy savings and user comfort. The current developments in this field can be seen from two perspectives; individual development of lighting control technologies and development of combined control ecosystems.

In terms of development of the technologies, there are new methods that are gaining focus in research. Instead of relying on already established methods of detecting occupation like PIR and ultrasound, researchers are focusing on improving detection using imaging systems and RFID, as discussed in a previous section.

Apart from development of individual technologies, researchers are putting emphasis on developing networks of sensors to overcome the faults associated with individual sensors. Wireless sensor networks are gaining focus in lighting control strategies. In these cases, instead of relying on data from a single sensor to detect occupancy, multiple sensors provide cumulative information on detection of occupancy, thus improving both energy efficiency and user satisfaction [73,74]. Tiller et al. [75] suggest through their research that instead of depending on a single expensive sensor, multiple inexpensive detectors in a network can provide much improved accuracy in detection, which in turn allows shorter time delay settings, and thus further energy savings.

Hybridization of control systems also seem to be a promising field as more and more researchers are mixing up various methods of control. Apart from the combination of common control systems, which has been discussed in the previous section, there are also several works which provide new hybrid control systems. One such scheme is a combined system that controls both the internal lighting level and level of daylight penetration using automated window blinds [49]. As mentioned already, excessive daylight entry can cause glare-related discomfort, despite the fact that more daylight availability could lead to more savings from artificial lamps. These control systems can make sure adequate amount of daylight enters the room without causing glare as well as controlling the dimming level of the interior lights at the same time. The system can be explained using the following flowchart (Fig. 5.) [76].

Combinations between multiple control strategies are becoming easier to achieve with the growing eminence of building automation platforms. Worldwide building automation has been standardized through the formation of the KNX standard [77]. This allows more than 300 electrical manufacturers to design their automation products using the same standards, making them compatible with each other. This is making the combination of various types of control technologies easy to combine by computer based programming without having to physically rewire the electrical layout [3,78].

A project by Dong et al. [79] tested a large scale wireless network system involving ambient sensing, carbon dioxide sensing and air quality sensing. Their work aimed to detect occupancy status and quantity using environmental parameters. Projects like this show that there are still less explored possibilities in sensing and control strategies that require novel research.

From the existing published works that have been reviewed in this paper, and combining them with further experimental analysis and simulations, an algorithm may be developed. This algorithm will take into account various parameters of a given area, e.g. room type, number of occupants, floor space, window area, orientation and provide useful information in choosing the best

Table 6
Savings from combined control systems.

Room type	Combination	Savings (%)	Reference
Office	Occupancy+ +daylight	46	Jennings et al. [34]
Office	Occupancy+ +daylight	68	Hughes et al. [36]
Office	Occupancy+ +daylight	49–63	Roisin et al. [20]
Office	Scheduling+ +daylight	38–61	Rubinstein et al. [71]
Classroom	Scheduling+ +occupancy+ +daylight	35–42	Martirano [72]

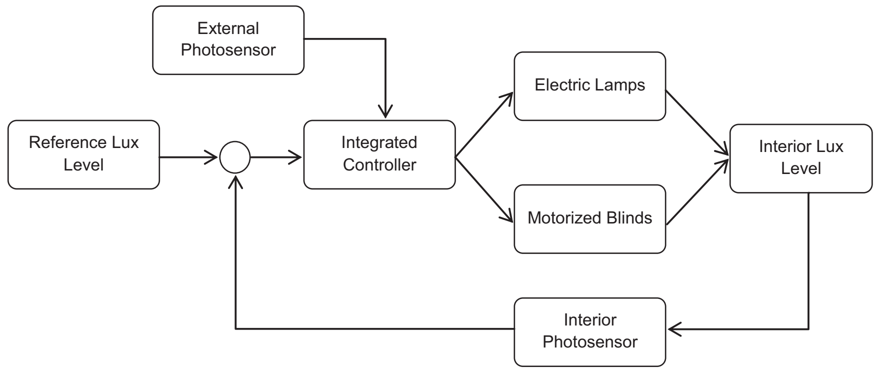

Fig. 5. Integrated control system for artificial lamps and daylight entrance [76].

control strategy. The algorithm may provide multiple options using single or multiple control systems and rate them in terms of energy saving potential. From the suggestions, the users can make an informed decision based on their energy saving target and project cost. Development of such an algorithm can be helpful in reducing the frequency of inappropriate application and tunings of control systems i.e. improve the effectivity of commissioning and lead to better user satisfaction.

7. Conclusion

It can be seen from the review that lighting control systems can provide significant energy savings and result in reduction in electricity costs. Decrease in electricity demand also has a positive environmental impact resulting from reduced carbon footprint. But each of the control technologies has various properties that affect their performance. Behaviour pattern of the occupants, geometric properties of the room or building, daylight entrance, type of work performed, etc. have profound effects on the lighting control systems, as seen from the discussions in this paper. Only by properly studying these factors, appropriate commissioning can be carried out that can lead to substantial energy savings as well as occupant satisfaction.

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